**UMTRA PROJECT DISPOSAL
CELL COVER BIOINTRUSION
SENSITIVITY ASSESSMENT**

October 1995

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**UMTRA PROJECT DISPOSAL CELL COVER
BIOINTRUSION SENSITIVITY ASSESSMENT**

October 1995

**Prepared for
U.S. Department of Energy
Environmental Restoration Division
UMTRA Project Team
Albuquerque, New Mexico**

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LIST OF ACRONYMS

<u>Acronym</u>	<u>Definition</u>
DOE	U.S. Department of Energy
EF	Emanation Fraction
EPA	U.S. Environmental Protection Agency
PVC	polyvinyl chloride
RAECOM	Radiation Attenuation Effectiveness and Cover Optimization with Moisture Effects
RRM	residual radioactive material
TAC	Technical Assistance Contractor
UMTRA	Uranium Mill Tailings Remedial Action

1.0 PURPOSE AND SCOPE

This study provides an analysis of potential changes that may take place in a Uranium Mill Tailings Remedial Action (UMTRA) Project disposal cell cover system as a result of plant biointrusion. Potential changes are evaluated by performing a sensitivity analysis of the relative impact of root penetrations on radon flux out of the cell cover and/or water infiltration into the cell cover. Data used in this analysis consist of existing information on vegetation growth on selected cell cover systems and information available from published studies and/or other available project research. Consistent with the scope of this paper, no new site-specific data were collected from UMTRA Project sites. Further, this paper does not focus on the issue of plant transport of radon gas or other contaminants out of the disposal cell cover though it is acknowledged that such transport has the potential to be a significant pathway for contaminants to reach the environment during portions of the design life of a disposal cell where plant growth occurs (Morris and Fraley, 1989). Rather, this study was performed to evaluate the effects of physical penetration and soil drying caused by plant roots that have and are expected to continue to grow in UMTRA Project disposal cell covers.

An understanding of the biological and related physical processes that take place within the cover systems of the UMTRA Project disposal cells helps the U.S. Department of Energy (DOE) determine if the presence of a plant community on these cells is detrimental, beneficial, or of mixed value in terms of the cover system's designed function. Results of this investigation provide information relevant to the formulation of a vegetation control policy.

2.0 STUDY SITES

UMTRA Project disposal cells are designed specifically for each site. The cover system addresses the specific residual radioactive materials (RRM) contained in relation to the topography, geology, seismicity, and climate of the selected disposal site. In addition, the soil and rock materials available in the area for construction of the cell are also accounted for in each disposal cell cover system design.

UMTRA Project disposal cells at Shiprock, New Mexico, and Lakeview, Oregon, were selected as the model sites. Shiprock represents a rock covered cell with a thick, relatively sandy radon barrier while Lakeview represents a vegetated covered cell with a relatively thin, clayey radon barrier (Figure 2.1). Both sites are located in arid to semiarid climates. While specific parameters from each site were manipulated to perform the sensitivity assessment, it must be remembered that the interpretations should be generalized to the potential effects of biointrusion to any disposal cell cover system, rather than assuming the results apply directly to that model site.

Volunteer plant growth has been observed on the disposal cell at Shiprock (Burt and Cox, 1993). The topslope of the Lakeview disposal cell was purposely seeded with crested wheat grass (*Agropyron desertorum*) and other grass species (DOE, 1990).

RRM (tailings) at the disposal cells under study are covered by a three-part system consisting of an infiltration/radon barrier (hereafter referred to as the radon barrier), a bedding layer, and a rock erosion layer. The radon barrier layer normally consists of a highly compacted soil layer with a high clay content placed at a specified moisture content so as to construct a compacted soil fabric that has a specified maximum hydraulic conductivity. The radon barrier layer is designed to limit radon emanation to the atmosphere from radioactive material within the cell to a level at or below U.S. Environmental Protection Agency (EPA) standards. The radon barrier is also intended to limit water infiltration into the tailings. The bedding layer is a mixture of sand and gravel engineered to support the rock erosion layer. The bedding layer prevents the rock erosion layer from penetrating the radon barrier and reduces or prevents erosion of the radon barrier. Finally, the rock cover layer (i.e., riprap) is designed to prevent water and wind erosion from adversely affecting the stability of the disposal cell. The rock cover on the topslope of the Lakeview disposal cell was filled in with soil and seeded with grasses.

2.1 SHIPROCK - SANDY COVER SITE

The Shiprock disposal cell is in northwestern New Mexico on the Navajo Nation. This arid site receives approximately 6 inches (15 centimeters [cm]) of rain per year. The Shiprock site is bordered on the northeast by the San Juan River and its associated floodplain. The floodplain supports cottonwoods (*Populus fremontii*), salt cedar (*Tamarix pentandra*), greasewood (*Sarcobatus vermiculatus*), and numerous species of annual and perennial forbs and grasses. The remainder of the site is bordered by disturbed land with a sparse vegetative cover (15 percent) that contains fourwing saltbush (*Atriplex canescens*), shadscale (*A. confertifolia*), Russian thistle (*Salsola kali*), summer cypress (*Kochia sieversiana*), Indian ricegrass (*Oryzopsis hymenoides*), several other grasses, and a few cactus species (DOE, 1984).

Figure 2.1
Typical Cross Sections

A) Shiprock, New Mexico, disposal cell

B) Lakeview, Oregon, disposal cell

The Shiprock disposal cell was completed in September 1986. A total of 1.1 million cubic yards (yd^3) (0.84 million cubic meters [m^3]) of RRM were stabilized in place within the 72-acre (ac) (29-hectare [ha]) disposal cell. The cover system consists of a 6.5- to 7.0-foot (ft) (2.0 to 2.1-meter [m])-thick compacted radon barrier, a 6-inch (0.15-m)-thick bedding layer, and a 1-ft (0.30-m)-thick rock erosion layer (Figure 2.1a). The topslopes of the pile have a 2 to 4 percent slope (from 50 ft [15 m] horizontal to 1 ft [0.30 m] vertical up to 25 ft [7.6 m] horizontal to 1 ft [0.30 m] vertical), while the sideslopes have a 20 percent slope (5 horizontal to 1 vertical). The bedding layer is mostly silty sand with some gravel. The rock on the sideslopes is smooth river rock 12 to 20 inches (30 to 51 cm) in diameter. The topslope is covered with cobbles 3 to 6 inches (7.6 to 15 cm) in diameter.

The Shiprock disposal cell was selected for this study because it has a rock-protected surface and its radon barrier is constructed of a rather thick sandy layer rather than a compacted clay layer frequently used in other UMTRA designs. The rock-protected surface limits evaporation and promotes local plant growth at the site; it was postulated that the sandy radon barrier may be thick enough to not be adversely affected by plant root penetration. For the generalized sensitivity analyses performed in this study, the Shiprock site is referred to as the sandy cover site.

2.2 LAKEVIEW - CLAYEY COVER SITE

The contaminated material at the Lakeview, Oregon, UMTRA Project site was stabilized at the Lakeview disposal cell, located in southern Oregon, approximately 7 miles (mi) (11 kilometers [km]) north of Lakeview. The Lakeview disposal site has a semiarid climate with an average precipitation of 16 inches (41 cm) per year (DOE, 1985).

The big sagebrush-antelope bitterbrush (*Artemisia tridentata* - *Purshia tridentata*) plant community is the dominant type around the site. Other frequently observed shrubs are low sagebrush (*Artemisia arbuscula*), gray rabbitbrush (*Chrysothamnus nauseosus*), green rabbitbrush (*Chrysothamnus viscidiflorus*), and mountain snowberry (*Symphoricarpos oreophilus*). Grass species are dominant in the understory, with species such as Idaho fescue (*Festuca idahoensis*), Canby bluegrass (*Poa canbyi*), Cusick bluegrass (*Poa cusickii*), Thurber needle-grass (*Stipa thurberiana*), and bluebunch wheatgrass (*Agropyron spicatum*) being the most common (WRD, 1985).

The Lakeview disposal cell was completed in October 1989. RRM totaling 943,000 yd^3 (721,000 m^3) were placed in the 17-ac (6.9 ha) cell. The cover consists of a 1.5-ft (0.46-m)-thick compacted clay radon barrier, a 6-inch (0.15-m) bedding layer, and a 1-ft (0.3-m)-thick rock erosion cover (Figure 2.1b). Soil was compacted into the rock layer on the topslope to form a rock/soil matrix. This matrix was planted with a grass mixture composed of crested wheatgrass, hard fescue (*Festuca* sp.), and big bluestem (*Poa ampla*) at a rate of 35 pounds (lb) of seed per acre (86 lb of seed per hectare) (DOE, 1990).

3.0 SHORT-TERM AND LONG-TERM PATTERNS OF PLANT GROWTH ON THE SHIPROCK AND LAKEVIEW UMTRA PROJECT DISPOSAL CELLS

This section analyzes plant communities that currently exist and are predicted to exist in the future on the Shiprock and Lakeview disposal cell cover systems. Information collected from the Shiprock and Lakeview disposal cell sites, in addition to information from existing literature, was used to evaluate the short- and long-term plant communities on the two cells along with characteristics of root development. From these data, potential short- and long-term estimated effects of plant biointrusion on the integrity of the radon barrier will be evaluated.

This analysis assumes plant succession will proceed, vegetation control measures will not be carried out, and early successional plant communities will have given way to later successional plant communities in 50 and 100 years at the Lakeview and Shiprock sites, respectively. In nature, the transition from early to late successional stages is a gradual process; the assumption that succession will take place in 100 years was made to simplify the analysis.

3.1 SHIPROCK DISPOSAL CELL

For this analysis, it is assumed that the early successional plant community is dominated by summer cypress and Russian thistle and that the late successional plant community is a saltbush-alkali sacaton association. The late successional plant community is dominated by various species of saltbush such as shadscale, Nuttalls saltbush (*Atriplex nuttallii*), matscale (*A. corrugata*), and fourwing saltbush.

3.1.1 Early successional plant community

Russian thistle and summer cypress are considered together in this section because they are both drought-tolerant annuals that invade disturbed sites. It is assumed that characteristics described for Russian thistle are also representative of summer cypress rooting patterns.

Plant height

Russian thistle grows up to 5 ft (1.5 m) in height while summer cypress can grow up to 7 ft (2.1 m) tall (Burt and Cox, 1993). Height is variable because the amount of precipitation received is an important factor. For example, Russian thistle grown in soil with 10 percent moisture by weight grew to 10 inches (25 cm) high while the plants grown at field capacity were 23 inches (58 cm) tall (Dwyer and Wolde-Yohannis, 1972).

Root depth

Russian thistle puts down roots at depths of 4 to 6 ft (1.2 to 1.8 m) (Reynolds, 1990; Wiese, n.d. a), while summer cypress can send roots down to 6.5 ft (2 m) (Foxy et al. 1984; Weise, n.d. b). Root depth is a function of the height of the plant, soil properties, and other factors. Excavations of summer cypress on the

Shiprock cell showed that 7-ft (2.1-m)-tall plants had roots at least 32 inches (81 cm) into the cover while 4-ft (1.2-m)-tall plants had roots up to 14 inches (36 cm) into the cover (Burt and Cox, 1993).

Root depth-to-shoot height ratio

The root depth-to-shoot height ratios for summer cypress and Russian thistle were not found in any of the available literature. Based on excavations at the UMTRA Project disposal cells, this ratio was less than 0.4 to 1 for summer cypress and 0.8 to 1 for Russian thistle (Burt and Cox, 1993). Given that these excavations did not determine the total root depth and that the maximum root depths and shoot heights are similar, the root depth-to-shoot height ratio for these species was assumed to be 1.0 to 1.

Lateral root spread

Russian thistle and summer cypress have lateral root spreads of up to 79 inches (200 cm) (Wiese, n.d. a,b). It is assumed that the ratio of root depth to lateral root spread is 1.0 to 1 for these two species.

Biomass

Biomass data were found for Russian thistle but not for summer cypress. Plants grown in 10 X 50 inch (25 X 130 cm) polyvinyl chloride (PVC) pipes had an average root biomass of 26 ounces (740 grams). Data for plants grown under controlled laboratory conditions for four water regimes are shown in Table 3.1.

Table 3.1 Shoot and root biomass for Russian thistle grown under four water regimes

Water content (%)	Shoot biomass (grams)	Root biomass (grams)	Total biomass (grams)	Root:shoot
Field capacity	33.0	7.6	40.6	1:4
50 capacity	28.3	8.6	36.9	1:3
20 capacity	14.5	4.0	19.5	1:3
10 capacity	9.2	2.7	11.9	1:3

From Dwyer and Wolde-Yohannis (1972).

These biomass values are based on an average of two plants in each replicate. In addition, root-to-shoot biomass ratios are similar for the four water regimes.

The changes in biomass with depth for Russian thistle have been determined by Klepper et al. (1985) (Table 3.2).

Table 3.2 Percent Russian thistle root biomass at four soil depths

Soil depth		Root biomass
(inches)	(cm)	(%)
1 - 20	1 - 50	72
20 - 39	50-100	22
39 - 59	100-150	5
59 +	150 +	< 1

From Klepper et al. (1985).

From these data, it can be seen that over 70 percent of the Russian thistle root biomass is in the top 20 inches (51 cm), while over 90 percent of the root biomass is in the top 39 inches (1 m) of the soil profile.

Soil and water relationship

Russian thistle and summer cypress are extremely drought tolerant species (Weise, n.d. a,b). Wolde-Yohannis (1972) determined that Russian thistle is more efficient in water use than various other species of desert grasses and shrubs and could survive at 10 percent of field capacity soil moisture (field capacity is the minimum moisture content where water drains in soil). Many drought tolerant plants can extract water from the soil at 30 bars of suction or greater. For this analysis, it is assumed that Russian thistle and summer cypress can extract water from soils at 30 to 60 bars of suction.

Cover plant community characteristics

Data collected at the Shiprock disposal cell and the information provided above were used to describe the plant community on the cell. In 1992, the early successional plant community on the Shiprock disposal cell was mapped in terms of areas of dense, moderate, and sparse vegetation. Using the site-specific data and information from the literature, various plant growth parameters were calculated (Table 3.3).

In 1992, an estimated 4.0 ac (1.6 ha) on the north slope of the Shiprock cell were covered with a dense growth of mostly summer cypress. The average height of the plants in the area was 20 inches (51 cm) (Burt and Cox, 1993). Based on the assumptions in Table 3.3, the average root depth and lateral spread was also 20 inches (51 cm). Assuming the 20-inch (51-cm) lateral root spread equals the radius of the circle of roots around the plant and using the formula for the area of a circle, the roots of an average summer cypress in the area of dense plant growth would cover 1256 square inches (8107 square centimeters [cm^2]). The estimated density of summer cypress was 73 plants per 100 square feet (ft^2) (9 square meters [m^2]) (Burt and Cox, 1993). Since it takes only 11 plants to fill an area this size with roots, it is likely that all the cover in the dense plant growth zone was filled with roots at least to the average rooting depth of 20 inches (51 cm). The actual rooting

Table 3.3 Characteristics of the early successional plant community on the Shiprock, New Mexico, disposal cell

Plant characteristic	Dense plant community	Moderate plant community	Sparse plant community
Number acres	4.0	4.4	63.6
Number plants per 100 ft ²	73	20	3
Average height (inches)	20	16	7
Average root depth (inches)	20	16	7
Average lateral spread (square inches)	1256	804	154
Percent ground with roots	100	100	3
Percent ground without roots	0	0	97

zone likely was deeper because 15 percent (about 11 plants per 100 ft² [9 m²]) of the summer cypress were anywhere from 30 to over 50 inches (76 to 130 cm) tall and likely would have rooted to the same depth. It was therefore assumed that under the conditions in 1992, the rooting depths where there was a fairly uniform distribution of roots were 40 inches (100 cm). The same type of analysis was performed for the areas of moderate and sparse plant growth, and it was determined that roots filled all the cover in the areas of moderate plant growth, and only 3 percent of the cover in areas of sparse plant growth (Table 3.3). In the moderately vegetated areas, the average rooting depth was 16 inches (41 cm) and this was assumed to be the maximum depth of uniform root distribution in these zones.

The zone of influence of the plants in the areas of dense and moderate plant growth includes the area covered by these types to a depth at least equal to the average rooting depth of all the plants.

3.1.2 Late successional plant community

The late successional plant community at the Shiprock site was assumed to be dominated by saltbush with shadscale and fourwing saltbush being the dominate species. As of 1992, these species have not been observed on the cell, although shadscale has been observed at the South Clive, Utah, disposal cell while fourwing saltbush has been observed growing on the Tuba City, Arizona, disposal cell (Burt and Cox, 1993). Salt cedar (*Tamarix pentandra*) is the only woody species observed thus far on the Shiprock cell. However, growing conditions for this species on the cell may decline over time because the annual plant species will dry out the radon barrier and it is assumed that salt cedar will not become a dominant species on the disposal cell in the future.

Plant height

Shadscale is a somewhat spiny shrub that grows from 1 to 3 ft (0.3 to 0.9 m) tall. Fourwing saltbush forms 2 to 5 ft (0.6 to 1.5 m) tall shrubs (Elmore, 1976).

Root depth

Shadscale maximum root depth was reported to be 39 inches (1 m) while fourwing saltbush roots at a maximum depth of 20 inches (0.5 m) (Benson et al., 1976). It was assumed the maximum rooting depth would be about 3 ft (1 m) into the 7-ft (2-m)-thick radon barrier if the saltbush plant community becomes established.

Lateral root spread

No information was found regarding the lateral root spread of shadscale and fourwing saltbush. The rooting pattern of shadscale is similar to big sagebrush in that it has a two-tiered system with a dense layer of roots in the upper strata and deeper layer of roots to extract water when the upper level of soil dries out (Caldwell, 1978). It was assumed that the ratio of rooting depth to lateral root spread is 2.0 to 1, similar to big sagebrush described further in Section 3.2.2.

Biomass

A study of plant communities in the Grand Junction, Colorado, area resulted in an estimated plant root biomass of 508 pounds per acre (lb/ac) (569 kilograms per hectare [kg/ha]) in a fourwing saltbush community, and 659 to 1441 lb/ac (739 to 1616 kg/ha) in shadscale-dominated communities (Benson et al., 1976). The moisture content of a rock covered UMTRA cell cover system should be more favorable (i.e., greater) than the Grand Junction study soils for a productive plant community because the rock layer acts as a mulch, which retains soil moisture. It was therefore assumed that the terminal plant community's root biomass in the cover would be 1430 lb/ac (1600 kg/ha). No information was available regarding the distribution with depth of shadscale or fourwing saltbush root biomass. Root profiles of these species indicate root biomass decreases rapidly for fourwing saltbush and more gradually for shadscale (Benson et al., 1976) with depth of root development. For this analysis, it was assumed that the root biomass decreases in a similar manner as big sagebrush described further in Section 3.2.2.

Soil and water relationships

Shadscale and fourwing saltbush are very drought tolerant species. Benson et al. (1976) determined that shadscale extracted water at an average of -50 bars and that the range was -23 to -95 bars pressure. This same study showed that fourwing saltbush extracted water at an average of -65 bars and had a range of -32 to -96 bars pressure (Note: Negative values of pressure are equal to positive values of suction).

Cover plant community characteristics

Cover plant community characteristics were developed for the existing plant community on the Shiprock cell (see Section 3.1.1). Such an analysis was not provided for the predicted late successional plant community.

3.2 LAKEVIEW DISPOSAL CELL

As noted earlier, the top slope of the Lakeview disposal cell was planted with various types of grass seed. The status of this plant cover was assessed from 1991 through 1993 (Burt and Cox, 1993; TAC, 1991; 1992; 1993). These observations indicated crested wheatgrass was the dominant plant species in 1991; however, drought conditions greatly reduced its numbers by 1993. Tall wheatgrass (*Agropyron* sp.), cheatgrass (*Bromus tectorum*), and tumble mustard (*Sisymbrium altissimum*) were the most common herbaceous species on the disposal cell cover in 1993. Big sagebrush began to invade the topslope in 1991 when three plants, all about 1 ft (0.3 m) tall, were observed. By 1992, there were six big sagebrush, two gray rabbitbrush, and two valley lupine (*Lupinus nanus*) on the topslope. All of these plants were 1 to 2 ft (0.3 to 0.6 m) tall.

The typical plant succession sequence leading up to a sagebrush plant community consists of annual weeds, mixed annuals-perennials, late annuals-perennials, and perennial grass. Such a sequence leading to establishment of a climax sagebrush community can take 40 years to occur under good conditions (Johnson, 1978). For this analysis, it was assumed that the grass- and herb-dominated plant community will persist for 50 years and the native sagebrush-antelope bitterbrush plant community then will become dominant. It also was assumed that crested wheatgrass will reestablish and become the dominant plant species in the early successional plant community. If this happens, it is probable that this plant community will persist for a long time. Observations at the Maybell, Colorado, UMTRA Project site near Craig, Colorado, have shown that the crested wheatgrass plant community that was established on the abandoned tailings pile in the early 1960s was still clearly the dominant plant species 30 years later. The Maybell site is surrounded by a big sagebrush plant community and only a few big sagebrush and rabbitbrush had invaded the site. In the area of the Lakeview disposal cell, it has been determined that big sagebrush invades crested wheatgrass plant communities slowly and attains good coverage in about 10 to 11 years (Corning, 1991). Therefore, it was assumed that the late successional big sagebrush-antelope bitterbrush plant community will be well established in 50 years.

3.2.1 Early successional plant community

Crested wheatgrass is native to the steppes of Asia. It was naturalized in the western United States and is used principally for rangeland rehabilitation. Following the decommissioning of some of the UMTRA Project sites, a thin layer of top soil was placed on the tailings piles and crested wheatgrass was planted. As indicated above, the Maybell UMTRA Project site was planted with crested wheatgrass in the early 1960s by the mill operator, and it is still the dominant species. This tendency to form monocultures for long periods of time has been observed by other

investigators (Marlette and Anderson, 1986) and may be the result of this species' ability to be a vigorous competitor for water and nutrients (Anderson and Toft, 1993).

Plant height

Crested wheatgrass varies in height depending on environmental conditions. The average height of this grass for three plants excavated in 1992 on the Lakeview disposal cell was 21 inches (53 cm), and for four plants in 1993 the average height was 26 inches (66 cm) (Table 3.4) (TAC, 1992; 1993). Observations over a three-year period indicated that the height of this species varied from approximately 7 to 30 inches (18 to 76 cm) (TAC, 1991; 1992; 1993).

Table 3.4 Average root depths and shoot heights for crested and tall wheatgrass, Lakeview, Oregon, disposal cell, 1992 and 1993

Plant species	Year	Number excavated	Average root depth (inches)	Average shoot height (inches)	Root-to-shoot ratio
Crested wheatgrass	1992	3	24	21	1.1 to 1
	1993	4	24	26	0.9 to 1
Tall wheatgrass	1992	4	24	32	0.8 to 1
	1993	2	38	33	1.2 to 1

Root depth

Crested wheatgrass has been reported to root at depths of 39 to 59 inches (1.0 to 1.5 m) (Abbott et al., 1991; Reynolds and Fraley, 1989). The maximum root depth observed in the Lakeview, Oregon, disposal cell was 24 inches (61 cm) (Table 3.4).

Root-to-shoot ratio

Data from the crested wheatgrass excavated from the Lakeview site indicated the root depth-to-shoot height ratio is about 1.0 to 1. However, as indicated above, this species has the potential to root much deeper than observed at the Lakeview site, so it is assumed that the root depth-to-shoot height ratio is 2.0 to 1, consistent with annual grasses in general (Fox et al., 1984).

Lateral root spread

Data regarding lateral root spread for crested wheatgrass is sparse. Reynolds (1990) indicates that lateral root spread for this species is 20 to 59 inches (50 to 150 cm) while Abbott et al. (1991) found that crested wheatgrass rooted 39 inches (1 m) deep had a maximum lateral root spread of 24 inches (60 cm), the ratio of rooting depth to lateral spread being 1.6 to 1. These figures are consistent

with the general ratio of root depth to lateral spread of 1.8 to 1 given by Foxx et al. (1984). For this assessment, the ratio 1.6 to 1 was assumed for crested wheatgrass.

Biomass

The estimated root biomass for crested wheatgrass grown in dirt-filled PVC pipes averaged 27 ounces (765 grams) (Reynolds and Fraley, 1989). Caldwell and Richards noted that 60 percent of crested wheatgrass root biomass is estimated to occur within the top 12 inches (30 cm) while 73 percent is within the top 20 inches (51 cm) of the root biomass (Table 3.5) (Reynolds, 1990).

Table 3.5 Distribution of crested wheatgrass root biomass by depth

Root biomass (%)	Soil depth (inches)	(cm)
35	1 - 6	1 - 15
25	6 - 12	15 - 30
13	12 - 20	30 - 50
13	20 - 31	50 - 80
13	31 - 39	80 - 100

Soil and water relationships

Crested wheatgrass is a drought tolerant species. Anderson et al. (1987) determined that this species extracted water from soil down to 10 to 12 percent volumetric moisture content (volumetric moisture content is the volume of water in a soil sample divided by the total volume of the sample). Anderson and Toft (1993) determined that crested wheatgrass extracted moisture to 13.3 percent by volume. Anderson et al. (1987) also determined that crested wheatgrass extracted water from the soil profile to a depth of 5.2 ft (1.6 m), and that it dried the soil to 10 to 12 percent soil moisture over the complete profile.

Cover plant community characteristics

It is assumed that the topslope of the Lakeview disposal cell is 100 percent covered by the crested wheatgrass dominated plant community. It is further assumed that the root depth-to-shoot height ratio for crested wheatgrass is 2 to 1, which means that crested wheatgrass that averages 2 ft (0.6 m) tall roots to a depth of 4 ft (1.2 m). It is also assumed that roots occur throughout this 4-ft (1.2-m) rooting zone, and are drying it out uniformly. The depth of the zone of influence of plants growing on the topslope of the Lakeview disposal cell is at least equal to the average rooting depth of crested wheatgrass plus a zone below the roots of approximately 32 inches (80 cm) that is dried out by the roots (Webb, 1994).

3.2.2 Late successional plant community

Big sagebrush covers about 3.9 million ac (1.6 million ha) in Oregon (West, 1978) and the big sagebrush-antelope bitterbrush is the common natural plant community surrounding the Lakeview disposal cell. Other frequently observed woody species are low sagebrush (*Artemisa arbuscula*), gray rabbitbrush, green rabbitbrush, and mountain snowberry (*Symphoricarpos oreophilus*). The most common grass species in the understory are Idaho fescue, Canby bluegrass, and bluebunch wheatgrass (WRD, 1985). It was assumed that this plant community would be well established on the cell cover within 50 years in the absence of vegetation control.

The assessment of plant growth and root characteristics presented below focuses on big sagebrush because it would be the dominant plant species and more information is published about this species than the other species that could grow on the topslope of the disposal cell.

Plant height

Plant height of mature big sagebrush is variable and depends on a variety of ecological factors. Tabler (1963) determined that 26- to 56-year-old big sagebrush growing in bottomland areas were up to 33 inches (84 cm) tall while 21- to 31-year-old plants in upland areas were up to 26 inches (66 cm) tall. The maximum height reported by Benson et al. (1976) from a study site near Grand Junction was 70 inches (1.8 m). Big sagebrush growing in the upper floodplain along the Dolores River near the Slick Rock, Colorado, UMTRA site were over 12 ft (3.7 m) tall (TAC, 1994).

Root depth

Root depth of big sagebrush can be quite variable. Local soil conditions have a considerable influence on root morphology (Tabler, 1963). The maximum rooting depth of 12 big sagebrush excavated by Tabler (1963) ranged from 48 inches (1.2 m) to 66 inches (1.7 m); most had sent roots 60 inches (1.5 m) into the ground. These were all mature plants ranging in age from 21 to 56 years. In Idaho, big sagebrush has been documented with root systems as deep as 88 inches (2.2 m) (Reynolds and Fraley, 1989). Three young, big sagebrush (1 to 3 years old) were excavated on the vegetative cover at the Lakeview site and the maximum root depth was 36 inches (91 cm) (Table 3.6).

Root depth-to-shoot height ratio

The root depth-to-shoot height ratios for big sagebrush was reported as 3.9 to 1 by Foxx et al. (1984). This ratio varies with location. Data from Tabler (1963) indicated that root-shoot ratios on exposed slopes and ridgetops averaged 3.7 to 1, while the ratio in bottomland areas was 2.1 to 1. The average root depth-to-shoot height ratio for the three big sagebrush excavated at the Lakeview site was 1.5 to 1. Two of the three excavations at the Lakeview site went down to the end of the plant's tap root, while the depth of the smaller roots and rootlets was not

Table 3.6 Root depth of big sagebrush excavated on the Lakeview, Oregon, disposal cell

Year	Root depth (inches)	Shoot height (inches)
1991	18	12
1992	21	17
1993	36	19

determined. The 1993 excavation represents the total root depth; the ratio was 1.9 to 1. For the purpose of this analysis, it is assumed that the root depth to shoot height ratio for big sagebrush growing on the Lakeview disposal cell is 2.0 to 1.

Lateral root spread

Lateral root spread for deeply rooted big sagebrush of up to 60 inches (1.5 m) has been reported (Sturges, 1978; Tabler, 1963). The ratio of root depth to root lateral spread for 12 big sagebrush ranged from 1.0 to 2.0 to 1 and averaged 1.4 to 1 (Tabler, 1963). The maximum lateral root spread of a big sagebrush rooted at 88 inches (2.2 m) was 39 inches (1.0 m) (root depth-to-root spread was 2.3 to 1). Another sagebrush rooted at 49 inches (1.2 m) had a maximum root spread of 26 inches (66 cm) and root depth-to-root spread of 1.9 to 1 (Abbott et al., 1991; Reynolds and Fraley, 1989). A higher ratio or root depth-to-root spread of 3.9 to 1 was given by Foxx et al. (1984). This analysis assumed the ratio of rooting depth to lateral root spread for big sagebrush was 2.0 to 1.

Biomass

The root biomass of big sagebrush in a sagebrush plant community near Grand Junction, Colorado, was estimated to be 1897 lb/ac (2127 kg/ha) (Benson et al., 1976) while the estimated root biomass in a site in central Washington was 2700 lb/ac (3000 kg/ha) (Mayland and Murray, 1978). It was assumed that the root biomass in the big sagebrush plant community would be 2700 lb/ac (3000 kg/ha), because the Washington study site may be most similar to the Lakeview site. Various studies have provided estimates of the percent root biomass with depth (Benson et al., 1976; Klepper et al., 1985; Tabler, 1963; Sturges, 1977). Based on this information, it was assumed that 50 percent of the roots of big sagebrush growing on the Lakeview disposal cell are in the top 12 inches (30 cm) and 75 percent are in the top 2 ft (60 cm) (Table 3.7).

Soil and water relationship

Big sagebrush occurs in semiarid climates or in arid climates where it can obtain additional water for at least part of the year (e.g., growing along arroyos). Big sagebrush has a two-storied root system with a dense network of roots in the

Table 3.7 Percent root biomass with depth for big sagebrush

1 - 12 (inches)	12 - 24 (inches)	24 - 36 (inches)	36 - 48 (inches)	48 - 60 (inches)	60 - 72 (inches)	72 - 84 (inches)
50%	25%	10%	8%	5%	< 1%	< 1%

upper 24 inches (61 cm) and a deeper system of roots below 24 inches (Sturges, 1978). The upper layer of roots extract water early in the growing season and as that soil dries up, the deeper roots start extracting water (Caldwell, 1978). Most of the root biomass is made of smaller roots less than 500 microns in diameter (Caldwell, 1978).

In Washington, the minimum soil moisture in a big sagebrush plant community was two percent by weight in the upper 16 inches (41 cm), and 4 to 5 percent below 16 inches (41 cm) (Rickard, 1967). In another study in Idaho, Anderson et al. (1987) determined that big sagebrush can extract water to 11 to 12 percent volumetric moisture content from a soil having a field capacity that was 20 percent by volume. Big sagebrush had an average internal water tension (i.e., suction) of -30 bars. The minimum measured tension was -19 bars and the maximum was -41 bars (Benson et al., 1976). Big sagebrush has been reported to extract water from the soil to a maximum of -60 to -70 bars (Caldwell, 1978). Anderson et al. (1987) reported that a natural sagebrush plant community extracted water to about 4.6 ft (1.4 m) and that the rooting profile was uniformly dry. In a study of transplanted big sagebrush, Anderson et al. (1993) reported that these plants dried out the soil profile uniformly throughout. Based on this information, it was assumed the big sagebrush plant community that may become established on the Lakeview disposal cell would uniformly dry out the soil profile throughout the rooting zone.

Cover plant community characteristics

Cover plant community characteristics were developed for the existing plant community on the Lakeview cell (see Section 3.2.1). Such an analysis was not provided for the predicted late successional plant community on this cell.

4.0 ANALYSIS OF PLANT EFFECTS ON SOIL PROPERTIES

The authors are well aware of potential radon transpiration by plants and of soil building processes that involve plants; however, this study's scope is limited to a simplified baseline evaluation of the magnitude of potential biointrusion effects on UMTRA Project disposal cell covers. A simplified sensitivity analysis was performed to "lower bound" the potential effects, so that an evaluation could rationally be made on whether additional study of the biointrusion process will be required.

For the purposes of this study, it was assumed that plant roots may penetrate the radon barrier, forming continuous holes. It was assumed that the biotic processes that assist formation of topsoil from subsoil or form soil from rock act too slowly to be considered. Analysis included the effects of roots penetrating the radon barrier, reducing the moisture content of the soil in the zone of influence of the roots, and increasing the soil porosity due to the formation of holes. Dying roots do not leave an empty hole in the soil; however, it was conservatively assumed that open, connected root holes are formed. Root holes were assumed to increase the porosity of the soil. Channeling or ducting of flow in the root holes was set aside for future study.

Drying of wet, uncompacted clayey soil can cause significant shrinkage cracking as anyone who has seen a dried lake bed can attest. Low-plasticity clay and sandy soil compacted near optimum moisture content as at the Lakeview and Shiprock sites has a small potential for shrinkage upon drying. These compacted soils also have a high shear strength and as a result resist crack formation upon drying. Therefore, shrinkage cracking was not considered in this study. When evaluating radon barriers constructed of high-plasticity clay compacted more than 3 percent wet of optimum moisture content, shrinkage cracking should be studied.

Primary soil properties of interest when designing a radon barrier include hydraulic conductivity and the radon diffusion coefficient. The radon diffusion coefficient may be considered to be a function of saturation, porosity, and dry unit weight (Rogers et al., 1984), but for a given soil, saturation is the predominant variable (Rogers and Nielson, 1991).

The hydraulic conductivity of a soil may be considered primarily a function of soil fabric, porosity cubed, and saturation cubed (Equation 4.1) (Mitchell, 1993).

$$K_H = CD_s^2 \left(\frac{\gamma_w}{\mu} \right) \frac{e^3}{1 + e} S^3 \quad (\text{Equation 4.1})$$

In Equation 4.1, K_H represents hydraulic conductivity. The first two terms on the right-hand side of Equation 4.1 (C and D_s^2) characterize soil fabric and grain size. The third term (γ_w/μ) characterizes fluid properties. For the analyses performed in this study of biointrusion effects, it has been assumed soil fabric does not change; the fluid is always water; and viscosity effects (i.e., caused by temperature changes) will occur whether or not vegetation is present. If these assumptions are correct, the first three terms in Equation 4.1 have a constant value. Additional discussion of the effects of soil structure is given below.

Of the soil parameters affecting hydraulic conductivity, soil fabric is the most sensitive. In the case of a radon barrier, the soil fabric is generated by a manmade process, because the soil layer is formed by the compaction of selected soil materials. To construct a radon barrier, first a suitable clayey or fine-grained soil is located in a borrow area. Next, the suitable soil is moisture-conditioned before (or just after) excavating, and hauled to the disposal cell. Then the radon barrier material is spread in relatively thin layers over the surface of the cell, and compacted by construction equipment such as a "sheeps-foot roller" or a "rubber-tired roller." Specified compaction density and fill consistency is accomplished by multiple passes of the compaction equipment over each lift of radon barrier soil.

A compacted soil's fabric may be relatively dry, loose and clumpy, or wetter, tighter, and plastic. The looser, drier soil fabric is called a flocculated structure, while the wetter, tighter, compacted fabric is called a dispersed structure (Leonards et al., 1962).

In a compacted soil having a flocculated structure, the clumps or clods of soil are relatively large and separated, and resist compressive stresses applied by compaction equipment (flocculated fabric) (see Figure 4.1). It takes placement of relatively thin lifts of fill and high amounts of compaction energy to compress these soil clods into a relatively impermeable soil layer.

Dispersed structure soils have smaller, more plastic clods (dispersed fabric) that require less compactive energy to compress them into a relatively impermeable soil layer (see Figure 4.1).

For this study, it has been assumed that root penetrations into a radon barrier layer compacted on the wet side of optimum moisture content will not change from a dispersed soil structure into a flocculated soil structure. This assumption may not be valid over a long period of time if small rootlets penetrate clods and flocs of soil making up the compacted soil structure. As these small rootlets grow, die, and grow again in yearly cycles, a buildup of organic matter in the soil occurs. Buildup of organic matter in the soil clods eventually may cause changes in soil chemistry that would reduce the plasticity of the soil and soil clod bonding, and could cause the radon barrier layer material to become more loose and friable. Such changes in soil fabric could increase the saturated hydraulic conductivity of the radon barrier layer, but these increases in hydraulic conductivity would only affect performance of the radon barrier if the barrier layer became saturated. Presence of living plants with extensive systems of roots and rootlets likely would prevent saturation of the radon barrier layer throughout most of its design life.

Potential long-term changes in soil fabric could cause increases in radon diffusion due to increases in porosity of the soil. These potential changes should be relatively insignificant so long as cover defects and desiccation cracks greater than 1 percent of the surface area are not formed (Rogers et al., 1984).

4.1 CALCULATION OF CHANGES IN THE RADON DIFFUSION PARAMETERS

Radon diffusion from disposal cells is modeled on the UMTRA Project with the Radiation Attenuation Effectiveness and Cover Optimization with Moisture Effects (RAECOM) computer code (Rogers et al., 1984). Several parameters are required

Figure 4.1
Compacted Soil Fabrics

Dispersed fabric

Flocculated fabric

FROM BARDEN AND SIDES, 1970.

for input to RAECOM (refer to Section 5.0); however, the parameters of interest when considering plant root penetrations into the radon barrier include 1) gravimetric water content of the radon barrier layer soil; 2) saturation of the radon barrier layer; 3) dry unit weight of the radon barrier layer soil; 4) radon diffusion coefficient of the radon barrier layer; and 5) porosity of the radon barrier layer. These parameters are not independent variables nor are they coupled by the RAECOM code. Each parameter was calculated separately and input into the program. A brief description of how each of these five parameters was calculated for use in the sensitivity analysis for each of four cases is given below.

Radon diffusion from the radon barrier layer was analyzed for four cases representing stages in the life of a disposal cell. These four scenarios, listed here for reference purposes, are detailed in Section 5.0.

Case 1 - Radon barrier layer "as built," with no plants.

Case 2 - Radon barrier layer "as designed," with soil moisture content reduced by 15 bar soil suction, no plants.

Case 3 - Disposal cell cover modified by early successional plant community.

Case 4 - Disposal cell cover modified by late successional plant community.

4.1.1 Gravimetric water content

In the first case, the average gravimetric water content of the radon barrier layer soil as constructed was obtained for the Shiprock and Lakeview sites from the MK-Ferguson completion reports (MK-F, 1987; 1991). The "as built" gravimetric water content for the Shiprock radon barrier was obtained from 1934 field tests, with a low value of 10.3 percent, a high value of 19.8 percent, and an average value of 14.9 percent. (The gravimetric water content of a soil sample is the weight of water in the sample divided by the weight of the solid particles in the sample.) The gravimetric water content of the radon barrier for the Lakeview site obtained from an average value of 75 tests was determined to be 40.5 percent.

For the second, third, and fourth cases where the soil suctions were increased to 15, 30, 60 bars, etc. (suction values were determined by plant analyses), the radon barrier's gravimetric water content was determined by using moisture-suction curves for the radon barrier soil from each site (Figures 4.2 and 4.3).

4.1.2 Percentage saturation

To determine the "as built" percentage saturation of the radon barrier soil, given values of the soil specific gravity (G) and unit weight are used to calculate the "as built" void ratio (e) (calculated as volume of voids divided by volume of solids in a cubic foot of soil). From the "as built" water content (w), the specific gravity (G), and the void ratio, the percentage saturation (S) is calculated from the equation $Se = wG$.

Figure 4.2
UMTRA Sandy Silt Cover Moisture Suction Curves

Figure 4.3
UMTRA Clayey Cover Moisture Suction Curves

MAC: NONSITE/BIOINTRUSION/MOIST SUCT 2

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Percentage saturation for the -15 bar case is calculated from the same values of e and G as the "as built" case, with a substitution of the -15 bar moisture content (w_{15}) in the equation.

After the plant biointrusion values of dry unit weight, water content, and void ratio are determined, the soil saturation for the third and fourth cases are calculated by using the same equation.

4.1.3 Dry unit weight (density)

Again, the "as built" and -15 bar values of dry unit weight and void ratio were given or calculated from values given in the Shiprock and Lakeview completion reports (MK-F, 1987; 1991). To calculate the plant modified dry unit weight and void ratio values for cases 3 and 4, it was assumed that the root hole volumes were added to the volume of voids in the soil and subtracted from the volume and weight of solids in the soil, thus increasing the void ratio and decreasing the dry unit weight of the plant-modified soil.

4.1.4 Radon diffusion coefficient

Radon diffusion coefficient values for the four cases were determined from the percentage saturation values for each case and radon diffusion saturation fraction curves for each site. A characteristic radon diffusion curve for a sandy-silt cover is presented in Figure 4.4.

4.1.5 Porosity

Porosity and void ratio (discussed above in Sections 4.1.2 and 4.1.3) are directly related. Porosity is the volume of voids in a soil sample divided by the total volume of the sample. Void ratio is the volume of voids in a soil sample divided by the volume of solids in the same sample. To calculate porosity (n) from void ratio (e), the following equation is used:

$$n = \frac{e}{1 + e} \quad (\text{Equation 4.2})$$

As discussed above in Section 4.1.3, the volume of root holes was added to the volume of the voids and subtracted from the volume of solids when calculating the change in void ratio, or porosity, used in cases 3 and 4.

4.2 CALCULATION OF CHANGES IN HYDRAULIC CONDUCTIVITY

Root data from Section 3.0 were used to determine the distribution and weight of roots in layers in the cover system. On the rock-covered, sandy radon barrier layer site, roots were assumed to start at the top of the radon barrier. Since the clayey cover site was purposefully vegetated from the surface of the rock layer by mixing topsoil into the surface of the rock (riprap) and planting crested wheatgrass, the root depths were calculated from the surface of the rock layer.

Figure 4.4
Radon Diffusion vs. Percent Saturation Sandy-Silt Cover

Since soil fabric was assumed to be a constant for these calculations, void ratio (e in Equation 4.1) and saturation (S in Equation 4.1) were the only variables that could change with root penetration into the radon barrier. Review of wood and root data indicated the roots have a minimum density of approximately 20 to 25 lb per cubic foot (lb/ft^3) (320 to 400 kg/m^3) (AITC, 1974). Using a density of 20 lb/ft^3 , the maximum estimated volume of roots in each zone was calculated conservatively using root weight distribution data from Section 3.0. Using the calculated volume of roots penetrating each layer of cover soil, it was assumed that the total volume of roots translated into an increase of void space. The increased void space was used to calculate an increase in void ratio and the $(e^3/(1+e))$ term in Equation 4.1. The $(e^3/(1+e))$ term was then calculated for initial conditions and with potential root conditions. These values of $(e^3/(1+e))$ then were compared by making a ratio of the term with roots to the term without roots. This ratio was multiplied by the original hydraulic conductivity value for the radon barrier layer to calculate the increase in hydraulic conductivity caused by root penetration.

The saturation term in Equation 4.1 was assumed to be equal to 1.0 (i.e., 100 percent saturation) because complete saturation would be a worst-case scenario for calculating cover infiltration.

Calculated increases for hydraulic conductivity caused by root penetration in the radon barrier layer were used to model increased infiltration into the model cells. These sensitivity analyses for increased infiltration are included in Section 6.0 of this report.

5.0 SENSITIVITY ANALYSIS: PLANT EFFECTS ON RADON DIFFUSION

5.1 SELECTED SCENARIOS

Radon flux from the cell was examined for four scenarios using both cell types.

5.1.1 Case 1

The first case was the "as built" condition. This initial performance case models the radon diffusion from the cell soon after construction is complete. This scenario assumes that no plant biointrusion has occurred.

5.1.2 Case 2

The second case analyzed was the -15 bar case with no plants. This scenario assumes that the radon barrier layer has dried out to a moisture content that would cause a soil suction or soil tension of -15 bars to be generated in the pore spaces of the radon barrier soil. Drying to a moisture content corresponding to a -15 bar soil tension presumably would take a very long time, if ever, to occur without the additional soil-drying effect of plant transpiration. A -15 bar case is the case analyzed in the standard UMTRA Project design procedure (DOE, 1989). Root holes are not considered in analyses performed using the -15 bar case.

5.1.3 Case 3

The third case assumes that an early successional plant community has developed. This case models root systems of early successional plants grown to a full depth plus a zone of soil drying that extends below the root bottoms an additional 80 cm (Webb, 1994). Russian thistle and summer cypress were assumed to dominate early successional vegetation developed on the sandy cover site (i.e., Shiprock), and crested wheatgrass was assumed to dominate the clayey cover site (i.e., Lakeview). For calculation purposes, gravimetric water content and saturation values were reduced to values that correspond to maximum suction values that could be generated by these dominant plants.

5.1.4 Case 4

The fourth case was analyzed to model the late successional plant communities at each site. The late successional plant community at the Shiprock site was assumed to be dominated by shadscale and fourwing saltbush, and at the Lakeview site by big sagebrush. As with the third case, an additional drying zone of 80 cm was added below the zones physically penetrated by the roots.

5.2 THE RAECOM MODELING CODE

Radon attenuation by the disposal cell cover was modeled with the RAECOM computer code. General diffusion theory along with its mathematics, discussion of the relevant parameters, and a FORTRAN code listing for RAECOM are included in

NUREG/CR-3533 (Rogers et al., 1984). This program requires that all input parameters are determined *a priori*. For instance, changing the moisture content of a layer will not automatically change the diffusion coefficient even though in a real world situation the soil moisture fraction does affect diffusion.

An example of the RAECOM input/output appears as Table 5.1. Seven parameters require input for each layer of a specified cell design. The thickness of each layer must be specified in centimeters. Porosity of the material is calculated from the measured dry bulk density and specific gravity. Moisture is measured as dry weight percent. The radon source term is determined by measurement of the radium-226 concentration. For design purposes, the barrier may be assumed to have a radium-226 concentration of zero. The emanation fraction (EF) typically is measured in the lab. It is a comparison of the radon activity in a sealed container (at equilibrium with its parent) to radon activity trapped in the mineral grains. The EF is then calculated as the difference between these two activities divided by the equilibrium radon activity. The diffusion coefficient also is normally determined in the lab, using representative samples of the subject material, and tested over a range of moistures, clustered around the expected long-term moisture values.

Regarding the scenarios considered, data for the layers below the radon barrier are as initially developed for purposes of cell design. Values for the diffusion coefficient, porosity, dry density, and percent moisture within the radon barrier are scenario-specific, determined as discussed in Section 4.0, "Analysis of Plant Effects on Soil Properties." The thickness for the barriers of sandy and clayey cells generally is as given in the original design. Radium-226 content is assumed to be zero. With a radium value of zero, the EF is also zero.

The last three columns in Table 5.1 are outputs based on the modeled input values. The output of interest is the radon flux. More specifically, the critical flux is the value determined for the designated radon barrier layer. In Table 5.1, this is the flux from layer No. 9. This value is actually the estimated average flux reaching the atmosphere above the radon barrier. As such, it is the value which is compared to the 20 picocuries per square meter per second ($\text{pCi}/\text{m}^2\text{s}$) standard set forth in 40 CFR Part 192. Both covers have sand bedding and riprap layers overlying the radon barriers; this material does have some attenuation value, but is ignored with respect to the radon barrier thickness. The flux from the radon barrier material is summarized for the various cases and cell matrices in Table 5.2.

5.3 GENERAL CONSIDERATIONS

The two cells used for the present study have very different radon/infiltration barriers. One is of a sandy matrix while the other is clay. Partly due to the less effective attenuating properties of the sandy matrix and partly due to the much higher radium concentrations (radium is the source term for radon generation) below the barrier, the sandy barrier must be considerably thicker.

Within the contaminated zone, the moisture values are much higher throughout the pile having the clay barrier. This in turn affects the diffusion coefficients in that higher moisture content tends to depress radon diffusion. Porosities are somewhat

Table 5.1 RAECOM input/output

RAECOBPC.BAS

OUTPUT INFORMATION : 10:32:10 06-14-1995
BOTTOM FLUX = 0 pCi/m²/sec
AIR CONC. = 0 pCi/l
BARE LAYER 1 FLUX = 64.41 pCi/m²/s
NO OPTIMIZATION APPLIED

L	THICK (cm)	POR	MOIST (%)	SOURC (pCi/g)	E.F.	DENS (g/cm ³)	DIFF COEF	FLUX (pCi/m ² /s)	CONC. (pCi/cm ³)	MIC
9	45.7	.54	40.45	0	0	1.23	0.00170	2.80	0.0	0.318
8	61.0	.59	54.2	54	.49	.92	0.10000	7.26	24.4	0.375
7	61.0	.61	59	33	.4	.86	0.10000	-5.32	25.2	0.384
6	61.0	.6	58.6	19	.4	.88	0.10000	-0.33	23.6	0.364
5	61.0	.62	60	15	.4	.84	0.10000	9.33	26.3	0.398
4	61.0	.58	54.5	15	.4	.94	0.10000	24.32	24.3	0.346
3	61.0	.63	58	199	.27	.91	0.01700	36.23	30.1	0.380
2	61.0	.58	51	94	.27	1.05	0.01700	3.61	34.2	0.317
1	243.8	.53	21	108	.27	1.18	0.01700	-4.91	69.9	0.654

***** TOP *****
- 9 - CLAYEY CAP/CASE 1: "AS BUILT", NO PLANTS IN Rn BARRIER *

- 8 - TOP OF "SELECT MATERIAL", CONTAMINATED (NON-TAILINGS) *

- 7 - "SELECT MATERIAL" *

- 6 - "SELECT MATERIAL" *

- 5 - "SELECT MATERIAL" *

- 4 - BOTTOM OF "SELECT MATERIAL", CONTAMINATED (NON-TAILINGS) *

- 3 - TAILINGS TOP *

- 2 - TAILINGS *

- 1 - TAILINGS BOTTOM *

***** BOTTOM *****

Table 5.2 RAECOM scenarios and resultant radon flux

Radon barrier		Resultant radon flux
Sandy matrix		
CASE 1	As built, no plants in barrier	2.9
CASE 2	As designed (-15 bar), no plants in barrier	15.6
CASE 3	Short term with early plant community	45.4 (20.5)
CASE 4	Long term with mature plant community	71.6 (44.2)
Clayey matrix		
CASE 1	As built, no plants in barrier	2.8
CASE 2	As designed (-15 bar), no plants in barrier	7.3
CASE 3	Short term with early plant community	40.8
CASE 4	Long term with mature plant community	38.6

- Notes: 1. Values are reported in picocuries per square meter per second; regulatory limit for average flux is 20 pCi/m²s.
2. Parenthetical values (XX.X) represent a plant density weighted average.

higher for the clayey materials. The clayey cell has very low densities for the slightly contaminated layers just below the barrier. This layer happens to be a light, pumiceous material containing a small percentage of organic solids (wood). These characteristics explain the low density and high porosity of this region.

It should be noted that neither the data provided for the RAECOM modeling nor the program itself includes any provision for radon flux via plant transpiration. It is unclear to what extent transpiration would increase the overall flux from a cell, or compete with the soil as a medium of transport, potentially resulting in a decrease of radon flux from the physical soil barrier itself. Certainly, there is evidence in the literature indicating that transpiration will result in removal of radon from the cell (Morris and Fraley, 1989). However, a comprehensive examination of this phenomenon and the synergism that may exist between transpiration and the parameters discussed herein, is beyond the scope of this assessment.

5.4 MODELING RESULTS - SANDY COVER

Both the first two "as designed" and "as built" scenarios yield flux levels that meet the 40 CFR Part 192 (20 pCi/m²s) requirement. The design case assumes -15 bar suction, resulting in a low radon barrier moisture value. During the actual placement of the tailings, measurements of important parameters indicated a higher moisture content, and, as would be expected, a lower average diffusion coefficient. This in turn leads to a very much lower surface flux in the "as built" case than in the "as designed" case.

The third and fourth cases consider the invasion of plants into the cell cover. The third case hypothesizes an early or short-term case. Case 4 examines the "worst

case" long-term scenario. The degree to which the cover is expected to be sparsely, moderately, and densely vegetated is considered; it is believed to change somewhat, tending to become more densely populated over time. Since RAECON does not compensate for this evolution, the results were modified by "area-weighted averaging." The -60 bar value was taken to represent dense vegetation, the -30 bar value to be equivalent to moderate growth, and -15 bar value taken to simulate sparse plant population which probably would be very similar to the no-vegetation design case. The projected relative percentages of population densities were multiplied by their respective flux values and then summed to approximate the final overall flux rates. Flux for the short-term vegetated state appears to be borderline at $20.5 \text{ pCi/m}^2\text{s}$ while the long-term case is problematic at $44.2 \text{ pCi/m}^2\text{s}$, given the modeled scenario.

5.5 MODELING RESULTS - CLAYEY COVER

Similar to the sandy cover cases, cases 1 and 2 for the clay-type radon barrier have flux values that are below the $20 \text{ pCi/m}^2\text{s}$ standard, with the "as built" scenario yielding a much lower radon flux value than the "as designed" -15 bar scenario.

The effect of biointrusion was somewhat different for these cases. The short-term vegetation community, crested wheat grass, already covers the cell completely; therefore no prorating was used in the final flux determination. The climax, long-term vegetation community was considered to be big sagebrush. It was assumed that these plants will develop a population density with plants coexisting in a state of mutually overlapping zones of influence. Consequently, the scenario is developed with "total cell coverage" by the plant community. Due to the soil characteristics, the soil is believed to be as dry currently as it is likely to ever become while the grasses still predominate. Thus, there is no significant difference in flux exiting the radon barrier under cases 3 and 4. Both values are estimated to be about twice the flux limit of $20 \text{ pCi/m}^2\text{s}$.

6.0 SENSITIVITY ANALYSIS: PLANT EFFECTS ON INFILTRATION

This section describes the estimated potential impact of biointrusion on infiltration through disposal cell covers. Both site-specific and generalized information were used as input to a simple mathematical model. This modeling was performed to estimate the long-term hydrologic performance of the covers due to enhanced cover permeability from root modification. For the scope of this sensitivity analysis, relative values were estimated that provide an upper bound value for infiltration.

6.1 COVER DESIGN DATA

Site characterization data used are from the Lakeview and Shiprock disposal cells (MK-F 1987; 1991).

6.2 MATERIAL PROPERTIES

A summary of physical and geotechnical properties of the layers in the Shiprock and Lakeview disposal cells is presented in Table 6.1.

6.3 HYDROLOGY

A summary of precipitation data for the Lakeview and Shiprock sites on a monthly basis during normal and abnormal (high) years is presented in Table 6.2.

Evaporation from open water surfaces is approximately 45 inches (110 cm) per year at Lakeview and 47 inches (120 cm) per year at Shiprock (Geraghty et al., 1973).

Normally, unsaturated conditions exist in the cell cover soils. The soils had a measurable moisture content at the time of placement, and that moisture content will normally fluctuate with time due to several causes. These include evaporation; transpiration; infiltration; a reduction in pore size, for example, by consolidation; and gravity drainage.

In the vadose zone (i.e., unsaturated zone) water is held in pore spaces due to capillary attraction. The maximum amount of water a particular soil can hold against the force of gravity is termed the field capacity. Water exceeding the field capacity is able to move through interconnected pores downward under the influence of gravity to either a zone of soils with a moisture content less than the field capacity or to a zone of lower hydraulic conductivity such that the water begins to build up and possibly move horizontally.

Flow is evaluated quantitatively according to Darcy's law (Freeze and Cherry, 1979). Darcy's law can be written for unsaturated flow in the x direction in an isotropic soil (i.e., soil that has equal properties in all directions) as

$$V_x = -K(\Psi) \frac{\partial h}{\partial x} \quad (\text{Equation 6.1})$$

Table 6.1 Summary of physical and hydrological properties of cover components potentially affected by biointrusion

Shiprock, New Mexico, site	Riprap	Bedding sand	Radon barrier	Tailings
Soil classification	GR	SM	ML/SM	ML
Mean grain size (inches)	6	0.01	0.001	0.001
Moisture content (%)	5	10	14.9	83.8
Hydraulic conductivity K (cm/s)	1×10^1	1×10^{-2}	1×10^{-7}	1×10^{-5}
Biomodified hydraulic conductivity ratio		1	a	1
Porosity			0.53	0.72
Specific gravity	2.65		2.70	2.23
Thickness of layer (ft)	1.0	0.5	7.0	-
Lakeview, Oregon, site				
Soil classification	GR	SM	CH/MH	SM
Mean grain size (inches)	6	0.01	0.0002	0.01
Moisture content (%)	5	10	40.5	83.8
Hydraulic conductivity K (cm/s)	1×10^1	1×10^{-2}	1×10^{-7}	1×10^{-2}
Biomodified hydraulic conductivity ratio	1	1	1.37	1
Porosity			0.54	0.72
Specific gravity	2.65		2.67	2.23
Thickness of layer (ft)	1.0	0.5	1.5	-

^aVaries with depth (from 2.15, 0.0' to 1.7'; from 1.27, 1.7' to 3.3'; from 1.07, 3.3' to 5.0'; from 1.03, 5.0' to 7.0').

ML – silt, low plasticity.

MH – silt, high plasticity.

GR – gravel.

SM – silty sand.

Table 6.2 Summary of precipitation information, Shiprock, New Mexico, and Lakeview, Oregon, sites

Value in inches	Shiprock site				Lakeview site			
	Mean precipitation	High	Year	24-hour maximum	Mean precipitation	High	Year	24-hour maximum
January	0.48	2.75	1974	2.00	2.52	5.81	70	1.78
February	0.39	1.81	1941	0.53	1.49	2.84	58	1.03
March	0.53	3.07	1938	1.00	1.45	3.84	71	1.22
April	0.38	2.11	1941	0.76	1.11	2.95	63	1.10
May	0.50	2.48	1941	1.34	1.67	4.12	71	1.35
June	0.30	2.63	1949	1.60	1.43	4.23	64	1.21
July	0.55	2.16	1957	1.31	0.20	0.98	58	0.47
August	0.91	3.34	1982	1.98	0.40	2.65	68	0.96
September	0.81	2.61	1940	1.27	0.65	1.98	71	0.89
October	0.83	5.03	1969	2.77	1.33	6.62	62	2.10
November	0.49	1.46	1974	1.08	1.98	4.59	70	1.14
December	0.54	1.79	1982	0.82	2.33	8.96	64	2.27
Total	6.68				16.56			

From Geraghty et al. (1973).

where ψ is the pressure head, $K(\psi)$ is a function relating unsaturated zone hydraulic conductivity to pressure head of water in the soil, h is the hydraulic head, and V_x is the specific discharge in the x direction. This equation is depicted in Figure 6.1 and shows that under a constant hydraulic gradient, the specific discharge increases with increasing moisture content. Because there is a direct relationship between pressure head and moisture content, such that when the moisture content equals the porosity (i.e., the soil is fully saturated), the unsaturated hydraulic conductivity equals the saturated hydraulic conductivity.

6.4 HYDRAULIC CONDUCTIVITY

For this investigation, saturated hydraulic conductivity is the primary soil property needed to assess potential infiltration effects due to biointrusion. Values of hydraulic conductivity for each soil layer were obtained from physical testing performed during construction by MK-Ferguson. Values for the hydraulic conductivity ratio of biointrusion modified to unmodified hydraulic conductivity values based on calculations of the $(e^3/(1+e))$ term in Equation 4.1 are presented in Table 6.1.

6.5 INFILTRATION CONCEPTUAL MODEL

A conceptual model is a description of an interpretation, or working description, of the characteristics and dynamics of a physical system (ASTM, 1995). For this

Figure 6.1
Characteristic Curves Relating Hydraulic Conductivity
to Pressure Head for a Naturally Occurring Sandy Soil

Freeze and Cherry, 1979.

consideration, the model domain is limited to the uppermost 10 ft (3 m) of the cell cover. An illustration of the upper materials is presented in Figure 6.2.

For this study, the transient unsaturated or partially saturated flow system can be simplified to examine only saturated flow. This simplification is made because, as shown above, the hydraulic conductivity is at its maximum under saturated conditions, thus allowing for maximum inflow under a specified hydraulic gradient.

A further simplification can be made by reducing the multiple cell cover layers to a single layer. The principle of continuity of mass states that in the absence of changes in storage within the layers, the specific discharge into the system must be equal to the amount leaving. This leads to a relationship where a single equivalent hydraulic conductivity may be used to represent a system of multiple layers

$$K_L = \frac{L}{\sum_{i=1}^n \frac{m_i}{K_i}} \quad (\text{Equation 6.2})$$

where K_L is the equivalent vertical hydraulic conductivity, m_i is the thickness of a layer, K_i is the layer conductivity, and L is the sum of the thicknesses of the layers (Freeze and Cherry, 1979). For this assessment, the bedding sand drain layer is assumed to be ineffective due to plugging and flow in all other directions and is also considered insignificant compared to the vertical direction.

Seasonal effects of precipitation and evapotranspiration have not been included in the comparisons made in this analysis.

The hydraulic gradient is calculated as if an infinite source of water is at the ground surface and is freely removed at the base of the radon barrier. This condition is conservative with regard to maximizing the infiltration since it essentially simulates the cell cover as continuously inundated with water ponding on the surface of the radon barrier.

6.6 MATHEMATICAL MODEL

The mathematical representation of the conceptual models is a vertical, one-dimensional model with a uniform hydraulic conductivity capable of simulating the saturated zone. The equation for flow is Darcy's law, as shown below:

$$Q = K(I)A \quad (\text{Equation 6.3})$$

where K is the saturated hydraulic conductivity, I is the hydraulic gradient, and A is the area through which the flow is directed. The hydraulic gradient is equal to the change in total head divided by the length over which the head acts.

Figure 6.2
Diagram of Conceptual Model

6.7 MODEL SCENARIOS

Table 6.3 presents a summary of cover layer properties calculated to be changed by plant biointrusion. These data were used to calculate increases in layer hydraulic conductivities. Table 6.4 presents a summary of input parameters for calculations of cover infiltration.

6.8 SENSITIVITY ANALYSIS

Two different calculations were performed to assess the sensitivity of the infiltration scenarios. These included considering water ponded at the ground surface without plant biointrusion and water ponded at the surface with an increase in the hydraulic conductivity due to plant biointrusion.

Ponded water

For the purposes of this study, water was assumed to be able to pond locally following substantial precipitation events. A ponded water depth of 0.5 ft (0.15 m) was used.

6.9 RESULTS AND DISCUSSION

The results of calculations are presented in Table 6.5. The calculated infiltration rate (Q) per square foot (0.0929 m^2) per day and per acre per day is presented, and so is the volume per acre per year. Also presented is the percentage change in infiltration rate from the normal (nonbiointrusion) evaluation to the case impacted by biointrusion. An estimate is included of the mean annual precipitation per acre per year and the mean annual evaporation from open-water surfaces per acre per year. This allows consideration of the maximum available amount of infiltration if all precipitation was allowed to infiltrate, and the maximum amount of evaporation, which would reduce the amount of water available for infiltration.

Shiprock

The calculated infiltration rate (Q) per square meter is 0.0123 liter [L] per day. This value increases 25 percent to 0.000154 L/m^2 per day due to possible biointrusion. Ponded water to a depth of 0.15 m would increase the flow rate to 0.000162 L/m^2 per day, an increase of 32 percent.

The infiltration rate (Q) also can be examined over a greater area and over a greater time period. Values are presented in Table 6.5 for an area of 1 ac and a period of 1 year. For the normal case without biointrusion, Q is 450,000 L and with the potential effects of biointrusion 564,000 L/ha per year. The mean annual precipitation is approximately 279,000 L/ha per year. This indicates that the model does not predict more inflow than that available from precipitation. However, the potential evaporation is 1,910,000 L/ha per year. The potential evaporation was derived from the mean annual evaporation from open water surfaces. This is considered the maximum available evaporation. However, it is reported in the

Table 6.3 Summary of physical and hydrological properties of cover components potentially affected by early successional plants, Shiprock, New Mexico, and Lakeview, Oregon, sites

Shiprock, New Mexico, site	Root zone 1	Root zone 2	Root zone 3	Root zone 4
Root mass (lb/ft ³)	1.37	0.43	0.11	0.05
Depth (ft) ^a	0 - 1.7	1.7 - 3.3	3.3 - 5.0	5.0 - 7.0
Initial volume voids (ft ³)	0.346	0.346	0.346	0.346
Final volume voids (ft ³)	0.415	0.367	0.352	0.348
Initial volume solids (ft ³)	0.654	0.654	0.654	0.654
Final volume solids (ft ³)	0.585	0.633	0.648	0.652
Void ratio:final	0.709	0.580	0.543	0.535
Biomodified hydraulic conductivity factor	2.15	1.27	1.07	1.03
Lakeview, Oregon, site				
Root mass (lb/ft ³)	2.24	1.60	0.63	0.00
Depth (ft) ^b	0 - 0.5	0.5 - 1.5	1.5 - 3.0	3.0 - 6.0
Initial volume voids (ft ³)	-	-	0.540	-
Final volume voids (ft ³)	-	-	0.572	-
Initial volume solids (ft ³)	-	-	0.460	-
Final volume solids (ft ³)	-	-	0.428	-
Void ratio:final	-	-	1.336	-
Biomodified hydraulic conductivity factor	1.0	1.0	1.37	1.0

^aDepth from top of radon barrier.

^bDepth from top of top soil filled riprap zone 3 is the 18-inch radon barrier layer which is biointrusion modified, zones 1 and 2 the riprap and sand bedding layers are not affected by biointrusion.

Dash indicates data not applicable to calculation.

Table 6.4 Summary of input parameters for cover components used in infiltration calculations, Shiprock, New Mexico, and Lakeview, Oregon, sites

	Unit/description	Shiprock site		Lakeview site	
		Normal case	Biointrusion case	Normal case	Biointrusion case
Layer, rr	riprap				
K_{rr}	cm/sec	1E+01	1E+01	1E+01	1E+01
m_{rr}	m	0.305	0.305	0.305	0.305
Layer, sd	sand bed				
K_{sd}	cm/sec	1E-02	1E-02	1E-02	1E-02
m_{sd}	m	0.152	0.152	0.152	0.152
Layer, rd	radon barrier				
Sublayer 1	1st root zone				
K_{rd1}	cm/sec	1E-07	2.15E-07	1E-07	1.37E-07
m_{rd1}	m	0.518	0.518	0.122	0.122
Sublayer 2	2nd root zone				
K_{rd2}	cm/sec	1E-07	1.27E-07	1E-07	1.37E-07
m_{rd2}	m	0.488	0.488	0.122	0.122
Sublayer 3	3rd root zone				
K_{rd3}	cm/sec	1E-07	1.07E-07	1E-07	1.37E-07
m_{rd3}	m	0.518	0.518	0.122	0.122
Sublayer 4	3rd root zone				
K_{rd4}	cm/sec	1E-07	1.03E-07	1E-07	1.37E-07
m_{rd4}	m	0.610	0.610	0.0914	0.0914
K_{rd}	cm/sec	1E-07	1.25E-07	1E-07	1.37E-07
m_{rd}	m	2.13	2.13	0.457	0.457
Layer ta	Tailings				
K_{ta}	cm/sec	1E-05	1E-05	1E-02	1E-02
m_{ta}	m	0.457	0.457	2.13	2.13
K_{eq}	cm/sec	1.426E-07	1.787E-07	6.667E-07	9.133E-07
m	m	3.048	3.048	3.048	3.048
H_{in}	m	3.048	3.048	3.048	3.048
H_{out}	m	0	0	0	0
I	m/m	1	1	1	1
Area	m^2	0.0929	0.0929	0.0929	0.0929

rr – riprap.

sd – sand bed.

rd₁ – radon barrier 1st root zone.

rd₂ – radon barrier 2nd root zone.

rd₃ – radon barrier 3rd root zone.

rd₄ – radon barrier 4th root zone.

ta – tailings.

m – layer thickness.

H_{in} – hydraulic head, in.

H_{out} – hydraulic head, out.

I – hydraulic gradient.

Table 6.5 Summary of results, Shiprock, New Mexico, and Lakeview, Oregon, sites

	Shiprock site			Lakeview site		
	Without biointrusion	With biointrusion		Without biointrusion	With biointrusion	
	Normal case	Normal case	Ponded water	Normal case	Normal case	Ponded water
Discharge (Q) per area						
m ³ /daym ²	1.23E-04	1.54E-04	1.62E-04	5.76E-04	7.89E-04	8.28E-4
gal/dayft ²	3.02E-03	3.79E-03	3.98E-03	1.41E-02	1.94E-02	2.03E-02
m ³ /dayha	1.23E00	1.54E00	1.62E00	5.76E00	7.89E00	8.28E00
ft ³ /dayac	1.76E01	2.21E01	2.32E01	8.23E01	1.13E02	1.18E02
Volume (V) per area per year						
L/ha	4.50E05	5.64E05	5.92E05	2.10E06	2.88E06	3.03E06
gal/ac	4.81E04	6.03E04	6.33E04	2.25E05	3.08E05	3.24E05
% change	-	25	32	-	38	44
Volume of mean annual precipitation (P) per area per year						
L/ha	2.79E05			6.89E05		
gal/ac	1.81E05			4.50E05		
Volume of potential evaporation per area per year						
L/ha	1.91E06			1.87E06		
gal/ac	1.25E06			1.22E06		

Dash indicates not applicable to calculation.

literature that rock covers reduce evaporation and potentially increase cover infiltration (Waugh et al., 1994; Valentin and Casenave, 1992)

Lakeview

The calculated Q per square meter is 0.000576 L per day. This value increases 38 percent to 0.000789 L/m² per day due to possible biointrusion. Ponded water to a depth of 15 cm increases the flow rate to 0.000828 L/m² per day, an increase of 44 percent.

Infiltration values are presented in Table 6.5 for an area of 1 ac and a period of 1 year. For the normal case without biointrusion, Q is 2,100,000 L/ha per year and with the potential effects of biointrusion 2,880,000 L/ha per year. The mean annual precipitation at Lakeview is approximately 689,000 L/ha per year and the maximum potential evaporation is 1,870,000 L/ha per year. This result is similar to the Shiprock site, even though the annual precipitation is substantially greater at Lakeview than Shiprock.

7.0 CONCLUSIONS

Plant biointrusion affects the radon diffusion coefficient and hydraulic conductivity coefficient differently. Reduced radon barrier layer moisture content increases radon emanations and decreases water infiltration. This is because unsaturated radon diffusion coefficients are higher than saturated values, and unsaturated hydraulic conductivities are lower than the saturated hydraulic conductivity. Plant transpiration may increase radon emanations, but it definitely reduces the water content of the radon barrier and decreases infiltration in compacted soils that are not cracked by drying. Saturation of a radon barrier maximizes its potential infiltration but minimizes its radon emanations.

Review of sensitivity analyses in Sections 5.0 and 6.0 shows that root penetrations into the radon barrier do increase the radon diffusion coefficient of the layer while the plants are alive, and root penetrations could increase the hydraulic conductivity of the radon barrier if the plants die and the roots rot out, leaving voids. The magnitude of these effects depends upon the types of plants that are growing on the covers, the depth of their root penetration and the areal extent of the impacted portion of the cover. While complete cell coverage by a plant community could produce unacceptable consequences, an impact evaluation must consider the area-weighted, integrated effect of biointrusion on the cell cover as a whole.

Some of the plants studied for these analyses may be considered to be "super plants." Although they are quite common in arid and semiarid regions of the southwestern United States, these plants are highly adapted compared to normal house or garden plants. These arid species can produce suction values to 60 bars or more, which means that they are nearly depleting all free water from the soil. To produce such high suction values, these plants must absorb salty water that would kill "normal" species. Since standard radon emanation calculations assume that the radon barrier would be dried out to -15 bar pressures, and not to -40 or -60 bars, these plants will locally (i.e., in their zone of influence) cause increased radon flux from the cell in areas where the cover is affected. Area-weighted calculations, including areas with sparse, medium, and heavy vegetation, considering an entire cell's surface may or may not give calculated average radon fluxes that exceed standards. To determine the potential effect of a given situation, such calculations would be required to be performed for each biointrusion-impacted site using site-specific parameters. The results of area-weighted calculations to evaluate the average effect of plant biointrusion on a given disposal cell are highly dependent on the distribution of radioactive materials in the cell and on the distribution of vegetated and nonvegetated cover areas.

8.0 RECOMMENDATIONS FOR FURTHER STUDY

Results of this study indicate that plant biointrusion can affect a radon barrier causing increased radon emanation when the barrier is unsaturated, or increased water infiltration when the barrier is saturated and the vegetation is dead.

To help quantify the effects of plant biointrusion on UMTRA disposal cells, the following recommendations are offered:

1. A plant survey should be conducted on all affected sites to determine the species of plants involved in early successional growth on each cell, the distribution of these plants on each cell, and a safe root-to-shoot ratio that can be used as an interim action indicator for initiating plant removal from the cell before the radon barrier is damaged.
2. An evaluation of all affected disposal cells should be conducted. This evaluation would include four components: a) evaluation of plant distributions and their associated root-to-shoot ratios, b) evaluation of the distribution of radioactive materials in the disposal cell, c) calculation of the biointrusion-affected radon diffusion from each radiological subarea, and d) calculation of the area-weighted radon diffusion from the entire cell to check for compliance with the 20 pCi/m²-s flux standard.
3. Using data derived from 1 and 2 above and the site-specific cover depth to the top of the radon barrier, calculate a maximum permissible height for the dominant plant species on each disposal cell. In the long-term surveillance plans, outline control measures to keep the critical plant species below their maximum permissible height.

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The following individuals contributed to the preparation of this document.

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